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STUDY OF NONLINEAR ACOUSTICS FOR THE PURPOSE OF PROCESSING SOP--ETC(U)
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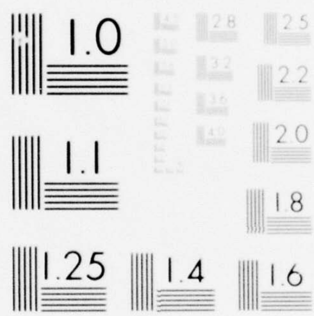

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER P-12121-E	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 STUDY OF NONLINEAR ACOUSTICS FOR THE PURPOSE OF PROCESSING 'SOPHISTICATED SIGNALS' 12		5. TYPE OF REPORT & PERIOD COVERED Final Report, 1 Jan 1974 - 28 Feb 1977
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 C. F./Quate H. J./Shaw		8. CONTRACT OR GRANT NUMBER(s) 15 DAHC04-74-G-0093 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS Edward L. Ginzton Laboratory Stanford University Stanford, California 94305		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 R&D Project No. & Title: D0161102B31E Rsch in Exper & Theo Electronics
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Research Office Post Office Box 12211 Research Triangle Park, North Carolina 27709		12. REPORT DATE 11 1 June 1977
		13. NUMBER OF PAGES 23
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 23 p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

18 ARO 19 12121.2-EL

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N/A

18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Acoustic arrays, digital processing, thermal imaging, acoustic scanning.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The work consists of two projects - one on the digital control of acoustic signals from an imaging array and the second on the use of acoustic signals to interrogate thermal images formed on an array of silicon bolometers. In the first project ithas been shown that in contrast to the present systems where analog systems are used to control the arrays in acoustic imaging multilevel digital processing systems can be employed to provide for the scanning and focusing of these arrays. The net result is an increase in performance and flexibility of these systems with images in real time. In the second part of

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20. ABSTRACT (continued)

the program we have shown that propagating acoustic signals can be used to interrogate an array of silicon bolometers which contain a thermal image. The theoretical and experimental results comprise a foundation for the construction of the thermal imaging device of the type described. The device should outperform existing uncooled thermal imaging devices over a practical range of frequencies.

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OUTLINE OF RESEARCH FINDINGS

The projects carried out under this program divide into two parts. Although they appear at first glance to be rather separate they do have a common base in that we are concerned both with the control of acoustic signals and the use of acoustic signals to process other forms of radiation. In the first part we summarize our work on the control of acoustic imaging arrays with digital signal processing. In the second section we summarize our work on the use of acoustic signals to read thermal images formed on an array of silicon mesas.

A. Control of Acoustic Arrays with Digital Signals

The purpose of this project was to introduce digital signal processing into ultrasonic, or acoustic, arrays. These systems use arrays of miniature acoustic transducers to produce and receive focused and scanned acoustic beams having resolution of the order of 1 mm, more or less. The arrays are basically analog devices. Under the project, we have studied the conditions under which multi-level digital signals can be used with these arrays.[1] The original objective was to design and construct a multilevel digital processing system of limited capacity sufficient to prove the principle, and to demonstrate this system in connection with modest acoustic scanning arrays which would be designed and constructed especially for this purpose. As the work progressed, it became increasingly apparent that the characteristics which were achievable with the digital processing systems under development had potential for increasing the performance and flexibility of virtually all acoustic imaging systems in existence in the laboratory, in addition to future systems which were either in the preliminary design stage or concept stage. In its final form it became concerned with the design of a full scale system for supplying the scanning signals, and processing the output signals, for the most complex one-dimensional, real-time acoustic imaging systems then existing or planned for the immediate future.

All imaging systems presently being studied in this laboratory use analog signal processing circuits for generating the control signals for the arrays. They use nonlinear mechanisms for producing the signal phases required for scanning receiver arrays. Under Grant No. DAHC 04-74-G-0093 we have designed a complete multi-level digital system, which we refer to as a multi-level digital delay line, which can replace the present analog circuits for performing these functions. It promises substantially improved accuracy over the analog systems, and reduce the image distortion and artifacts. The digital system should possess great flexibility and provide for variable scanning rates, new types of scanning patterns and scanning protocols which capitalize on the particular characteristics of different objects which are being scanned.

The acoustic transducer arrays used in scanning systems are analogous to the antenna elements in phased array antenna systems. However, the acoustic arrays are operated such as to produce electronic focusing of the acoustic beam with electronically variable focal length, in addition to acoustic steering and scanning of the beam. The signals required by these arrays and the beams formed by these arrays are essentially analog in character. Thus, while standard binary digital electronics can be used in the early stages of the electronic sections to produce the signals required by the arrays, they cannot be used in the later stages which interconnect with the arrays themselves. The array signals can be approximated by digital binary waveforms in certain cases. An experiment of this kind was carried out in the early stages of the present project. In that experiment the transducer array operated as a linear Fresnel phase plate in which each element of the array had the same signal amplitude, and had either one of only two phases, namely zero of π. This type of operation was demonstrated when we constructed an experimental imaging system consisting of a linear transmitting array of 32 PZT transducer elements operated at a frequency of 1.8 MHz and controlled by binary integrated circuit electronics.[2] This work showed good agreement between theoretical and measured imaging performance. It was shown that the beam from the phase plate can be accurately focused and scanned with binary signals. However, superimposed upon the focal spot is a wide angle radiation of relatively high level which is common to two-level phase plate systems. The purpose of this first experiment was to gain experience with digital control of PZT array elements and to demonstrate a correspondence between theory and practice. We then proceeded to multi-level discrete signals, to remove the limitations imposed by two-level focusing.

In the digital delay line, binary digital circuitry is used in the early stages, and this is fanned out into later stages which generate multi-level discrete signals. Analysis has been performed under the project to determine the number of discrete levels required to preserve all of the image information. Calculations were made for systems employing 100 elements in the scanning arrays, which represent the largest number under consideration at this time.[1]
These systems provide 100 resolvable spots per line scan in the image.
We have found that 5 bit electronics, which provide 32 discrete phase levels for each of the elements in the arrays, will accomplish this purpose. We have designed and tested phase generators which generate stable rf signals having

32 fixed phase values for use with these systems. These operate over the range of 1 to 10 MHz, generating signals having the required phase values at any desired frequency within this range. This will extend the operating frequency range of the acoustic imaging systems, allowing them to operate anywhere within the 1 to 10 MHz frequency range, depending upon the frequency bandpass characteristics of the PZT arrays themselves. The digital delay line can deliver any desired phase and amplitude independently to each of the 100 elements in the transmitting and receiving arrays of the imaging systems. Command signals which determine scanning rates, focal depth, focal spot size, scanning mode, and other functions are fed into the input channels of the digital delay line, which accept standard binary inputs. These command signals are generated in a micro-computer. The entire imaging system is thus controlled by keying the appropriate words into the micro-computer. In effect the digital delay line establishes, at its 100 output terminals, a series of rf signals having prescribed values of amplitude and phase. This distribution is shifted along the array of terminals to accomplish the beam scanning of the transducer array whose elements are connected 1-to-1 to these terminals. It is thus analogous to a delay line having 100 equally spaced taps.

We have breadboarded two channels of this 100 channel system and used it to check out the basic design and also to obtain quantitative information on the effect of cross-talk between adjacent channels. The results of these tests have been satisfactory and are included in the technical report.[1] This was followed by completion of the electrical and mechanical design for the final 100 element digital delay line. This is also included in the technical report. The first prototype engineering version of the complete system, using this design, will be constructed under auspices of another program in the laboratory concerned with the development of complete acoustic imaging machines.[3] This will be accomplished by procuring commercially produced PC boards manufactured according to the layouts developed above under the present program. In that system miniature transformers are used to match the electrical impedance of the PZT transducer elements with the impedance of the coaxial lines. The acoustic head of the imaging system contains only the PZT array and its transformers, allowing a compact design, which can be oriented and moved at will with relation to the objects being imaged. In both non-destructive testing and medical applications it is found increasingly important to minimize the time required to obtain completed detailed images. The electronic scanning approach allows time reductions over present manual mechanical scanning procedures. Beyond that, further substantial time reductions are expected to result from employing multiplexing patterns in the scanning of the beam, which are not possible with the present analog control systems and analog tapped delay lines, but which are within the capability of the new digital delay line. It has been found under other programs in the laboratory[3] that different types of samples, e.g., samples of high acoustic transparency, samples with high acoustic attenuation, samples with planar surfaces, samples with high Q internal acoustic resonances, require different modes of adjustment of the imaging system. It is expected that the digital delay line will increase the generality with which such images can be obtained in addition to improving the accuracy in any given mode. Most of the imaging systems involved in the work of this laboratory are concerned with nondestructive testing (NDT) and nondestructive evaluation (NDE) of materials and structures. The detailed natures of the objects to be studied are varied and the flexibility of the digital delay line will be important.

B. Propagating Acoustic Signals as a Method for Interrogating Thermal Images

A new type of uncooled thermal imaging device has been investigated under this project. The device consists of an array of semiconductor bolometers scanned by a piezoelectric acoustic delay line. The scanning is done by charging the surface of each bolometer by means of a strong rf pulse on the delay line, and observing the rate of decay of the surface charge; this rate is strongly temperature dependent. The detailed theory of operation of the device has been developed, including the processes of surface charging and discharging, acoustic attenuation as a function of the semiconductor's surface charge, thermal design problems, and noise processes.[4] The fundamental principle of operation and the practicability of meeting some thermal design requirements were verified experimentally using silicon bolometers adjacent to a lithium niobate delay line.

The significant theoretical findings are as follows: the charging process takes place through a non-linearity in the surface majority carrier concentration vs. applied field. Because of the non-linearity, a large ac field, such as is produced by a 3 watt per centimeter acoustic pulse on lithium niobate, causes a substantial increase in the surface carrier concentration at the silicon surface. The excess carriers are then trapped in surface states. The discharge process should be controlled by minority carrier generation in the space charge region, at least for silicon. A new theory of acoustic attenuation by a depleted semiconductor has been completed and it indicates that the main source of attenuation is the release of majority carriers by charged surface states. The predictions of this theory are in considerably better agreement with experiment than those of previous theory, which did not account for the effect of surface states. The noise performance of the device should be limited by background quantum noise and by statistical variations in surface state occupation. The low frequency detectivity of the device should be 2×10^{10} centimeter per watt in a 1 Hz bandwidth, but would have a cutoff frequency less than 0.1 Hz for a typical device. By making 0.25 micron thick bolometers it should be possible to raise this frequency to 5 Hz .

The experimental findings show that the basic description of the device's operation is correct. In particular, the surface state charge is discharged by the generation of minority carriers and we should achieve the expected temperature sensitivity. Also, it has been shown that bolometers can be built with power sensitivity approaching the theoretical limit if we are prepared to support the bolometers with small photoresist spacers.

In this work we have described a fundamental new type of thermal imager which consists basically of an array of silicon bolometers. The temperature of each bolometer is determined by indirectly measuring the temperature-sensitive generation rate of electron hole pairs in the silicon. The extremely high thermal resistance - 1.6×10^{7} °K for 100μm x 100μm detectors - required for the best performance of the device makes it attractive to use a measurement technique that does not require physical contact to the bolometers, particularly contact with metal conductors.

The technique first proposed and used for the acoustically scanned visible imager[5,6] fills this requirement. That technique depends on the change with depletion width of the acoustic attenuation induced by a semiconductor near an acoustic delay line, and on the ability of the fringing fields of a high-power acoustic pulse to charge the silicon surface. We examined the physical details of the charging, discharging, and attenuation processes. The significant findings were as follows:

(a) The charging process takes place because of the non-linearity in the surface electron concentration with applied field. Because of this non-linearity, a large ac field causes a substantial increase in the surface electron concentration, and thence in the trapping rate. An acoustic power density of 3W/cm is more than sufficient to ensure full charging of the surface states by this mechanism.

(b) The discharge process is controlled by minority carrier generation. In the thermal imager this takes place in the space charge region; in the visible device it takes place mainly in the neutral bulk. An important point to note in either case is that emission from the surface states is not important.

(c) The attenuation caused by the depleted semiconductor arises from the release of majority carriers by charged surface states. A comparison of the experimentally measured attenuation and that predicted from this viewpoint shows vastly improved agreement over that with previous theory.

We examined the special physical problems which must be solved to obtain a sensitive device. By operating the bolometers in a 1μm of Hg vacuum and using carefully designed mechanical support structures, it should be possible to obtain ideal sensitivity, limited only by the optical system and the immutable laws of blackbody radiation.

All of that work comprises a solid theoretical foundation for the design and construction of a thermal imaging device. We have also carried out some of the experimental tests for that foundation. The model of surface state discharge by space charge generation current is verified, and we show that the scheme of bolometer support by photoresist feet is workable. Actual measured thermal resistances are within the range of theoretical expectation.

We have examined the device sensitivity and noise from a theoretical standpoint. A survey of potential noise generating mechanisms indicates that only the background limited quantum noise, and variations in surface state occupation, are important in a practical device.

If this indication is correct, then it is incontrovertibly possible to build an imaging device with a respectable low-frequency detectivity - 2×10^{10} cm $Hz^{1/2}$/W. The main problem with such a device is its poor response to time varying input power. This poor response comes about because of the thermal mass of the silicon bolometers. It may be possible, using emerging silicon processing technology, to make very thin bolometers - as thin as $0.25 \mu m$. These devices would have fast response times, in conjunction with inherently small low frequency noise. As detectors, they should outperform existing uncooled devices.

SCIENTIFIC PERSONNEL SUPPORTED AND DEGREES AWARDED

DURING THIS REPORT PERIOD

Calvin F. Quate	-	Principal Investigator Professor of Applied Physics and Electrical Engineering
H. John Shaw	-	Edward L. Ginzton Laboratory Adjunct Professor by Courtesy of Department of Applied Physics
Kenneth N. Bates	-	Research Assistant
Thomas W. Grudkowski	-	Research Assistant Ph.D. Degree received May 1975.
Nicolas J. Moll	-	Research Assistant Ph.D. Degree received June 1977.

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BIOGRAPHY

C. F. QUATE

Calvin F. Quate was born in Baker, Nevada. He received the B.S. Degree in Electrical Engineering from the University of Utah in 1944 and the Ph.D. Degree from Stanford University in 1950. In 1949 he joined the technical research staff at Bell Laboratories in Murray Hill, New Jersey, where he was later appointed Associate Director of Electronics Research. He joined Sandia Corporation in Albuquerque, New Mexico, in 1959 and in 1960 became Vice-President and Director of Research. Stanford University appointed him Professor of Applied Physics and Electrical Engineering in 1961; in the autumn of 1969 he assumed the Chairmanship of the Applied Physics Department at Stanford and held this position until August 1972. In the Spring of 1970 he was elected to membership in the National Academy of Engineering. From September 1972 until March 1974 he served as an Associate Dean in the School of Humanities and Sciences at Stanford. In the spring of 1975 he was elected to membership in the National Academy of Sciences.

Dr. Quate's major research interest is in the field of acoustic imaging. He is the author of more than 70 scientific publications.

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